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Development of Durcon, An Expert System for Durable Concrete: Part I

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

ABSTRACT

This is a progress report on the development of DURCON an expert system to give recommendations on the selection of constituents for durable concrete. Four major concrete deterioration problems will be covered when the DURCON system is completed; freeze-thaw, sulfate attack, corrosion of reinforcing steel, and cement-aggregate reactions. The factual knowledge base for DURCON is based on the American Concrete Institute Guide to Durable Concrete. Heuristic knowledge is being obtained from experts on the durability of concrete. The approach being taken in developing DURCON is discussed. Then a model expert system for concrete exposed to freeze-thaw conditions is described.

Keywords: aggregate, artificial intelligence, concrete, corrosion, durability, expert system, freeze-thaw, knowledge-based system, sulfate attack

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1. INTRODUCTION

Among the most active research areas in artificial intelligence during the past 20 years has been the development of expert systems, which also are known as knowledge-based systems. At first, expert systems were primarily of academic interest, with little attention being given to their practical applications. The usefulness of expert systems in solving difficult practical problems, however, has become recognized and their development is being pursued in many fields. For example, expert systems have been developed to give recommendations in such areas as medical diagnosis [1], molecular structure identification [2], mineral exploration [3], computer configuration [4], and structural analysis [5]. An expert system should be able to give recommendations at a level comparable to, or above, an expert. Expert systems are most useful when the knowledge is based on heuristics and when mathematical relationships are not available, which is often the case in the construction field.

The knowledge required to solve difficult problems encountered in the construction industry is not often readily available to the field engineer or designer. Further, when information is accessible it is often too imprecise to be of substantial assistance in solving specific problems. Until now the construction industry had to depend on a relatively few well-qualified experts to give recommendations on problem resolution. Expert systems appear to be an effective tool for preserving and maintaining the knowledge of experts and for using it in solving difficult problems. Research on the applications of expert system to construction problems primarly has been carried out by Carnegie-Mellon University [6] and the U.S.-Corps of Engineers [7]. Undoubtedly, the construction industry will soon begin to more fully exploit the benefits of expert systems.

This report discusses the early stages in the development of DURCON (DURable CONcrete), a prototype expert system which is intended to give recommendations on the selection of constituents for durable concrete. The purpose of developing DURCON is to demonstrate the application of expert systems to improving the process of selecting construction materials. Concrete was selected as the subject of this prototype system as it is the most widely-used man-made construction material. In the United States alone, over 700 million tons of concrete are placed each year [8]. It is well-known that major problems encountered in the durability of concrete can be significantly reduced by improved selection of concrete constituents and concrete design. Development of DURCON is feasible because of the large amount of specialized factual and heuristic knowledge which exists on relations between the design of concrete mixtures, including the constituents, and the durability of concrete.

2. PRINCIPLES OF EXPERT SYSTEMS

An overview of expert systems is presented in this section to introduce the concepts involved in the development of DURCON. More comprehensive views of expert systems are given in references 9, 10, and 11.

2.1 Features of Expert Systems

In the several definitions given for the term "expert system," the essential concept expressed is the use of the knowledge of experts to solve difficult problems. Feigenbaum [12], a pioneer in expert systems, gave the following definitions in which the main concepts are presented:

> "An Expert System is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution. The knowledge necessary to perform at such a level, plus the inference procedure used, can be thought of as a model of the expertise of the best practitioners in the field."

The knowledge of an expert system consists of facts and heuristics. Facts constitute information that is widely accepted to be valid and readily available (e.g., in textbooks). Heuristics are rules of good judgement or rules-of-thumb [13]. Often an expert will rely upon his own judgement (heuristics) to solve problems because of the lack of well-understood theories or facts.

2.2 Architecture of an Expert System

An expert system is an interactive system consisting of three major components (fig. 1):

(1) A <u>knowledge base</u> of facts and heuristics which can be applied to a specific case.

(2) A <u>global data base</u> (working memory) which contains, in temporary storage, observations or evidence provided by the user about a specific case, and all derived information about the case.

(3) A <u>control system</u> or inference engine which selects the appropriate knowledge rules and recommendations for the solution of the problem.

Other features usually present in expert systems are:

- explanatory interface which permits the user to understand why certain questions are asked and gives a justification for specific conclusions or recommendations

- transparency of the computer program to the user (i.e., the user does not become involved in programming).

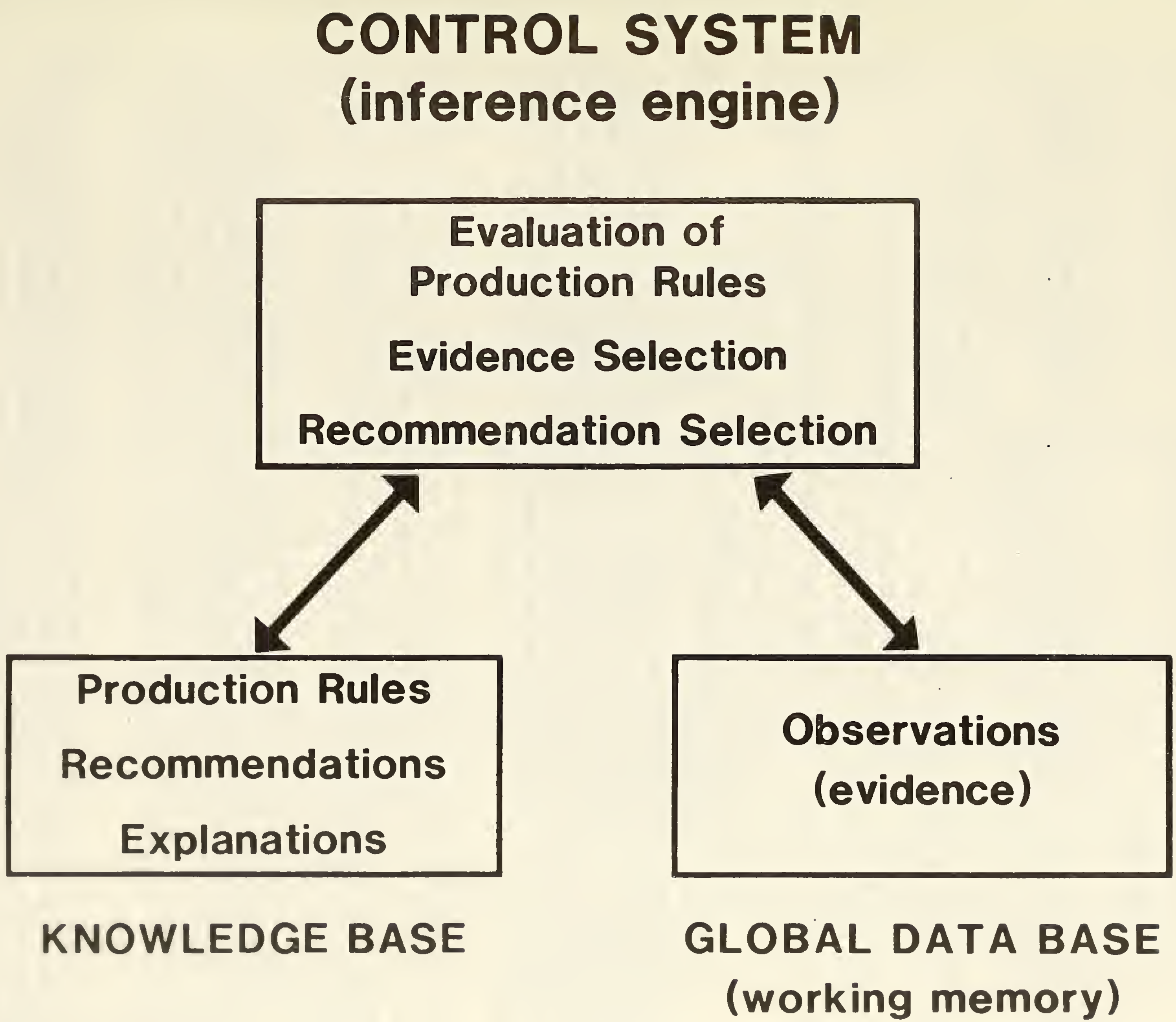

Figure 1. Major Components of an Expert System

- modification of the computer program can be accomplished without a comprehensive re-programming, e.g., portions of the knowledge base can be modified without the need for other restructuring.

2.3 Knowledge Base

The ability of an expert system to solve a problem (referred to as its "power") has been observed to increase with the extent of its domain (subject specific) knowledge. Undoubtedly the most demanding phase of developing an expert system is obtaining and representing relevant knowledge.

The domain knowledge of an expert system is often represented by production rules which have the general form:

If: Logical conditions are satisfied (antecedent) (1)
Then: Take the indicated action (consequence)

These rules are further illustrated by the following rule taken from DURCON

If: (1) Severe freeze-thaw conditions are anticipated and
(2) The nominal size of aggregate is 3/8 inch (9.5 mm.)
Then: The percent of entrained air should be 7.5 (2)

An expert system usually has many judgmental or empirical rules (heuristics) which lead to recommendations or conclusions which contain a certain level of uncertainty. A numerical value (certainty factor) can be given to each rule to indicate the degree of certainty. These certainty factors can be combined with each other to obtain an overall certainty factor for the final recommendation or conclusion. Certainty factors are measures of the confidence that can be placed in any given conclusion or recommendation.

2.4 Control System

The control system decides which production rules should be invoked and it must resolve any conflicts which may occur if several rules are satisfied. There are two main approaches for evaluating production rules: backward chaining and forward chaining [9, 11].

In backward chaining the system has a set of initial goals, such as solutions to a problem. The rules are invoked in reverse order, with the right-hand sides of the rules stating possible goals, and the left-hand side of the rules being examined to determine which goals are satisfied i.e., consistent with the evidence. The goals are proven or disproven until the "most-correct" solution is obtained. Backward chaining is often used in diagnostic systems e.g., MYCIN [1].

In forward chaining the system does not start with any defined goals. Instead the system starts with a set of evidence and proceeds to invoke the rules in a forward direction (antecedent first), continuing until no further production rules can be invoked. Forward chaining is often used in systems providing recommendations on design related problems.

3. APPROACH FOR DEVELOPING DURCON

The acceptance of an expert system undoutedly depends on the credibility of its knowledge base. In the conceptual design of DURCON, three criteria were established for selecting the main source for the factual portion of the knowledge bases. The facts should have been: (1) agreed upon as the consensus of a team or committee of experts on the durability of concrete; (2) published so that the concrete community could judge their reliability; and (3) accepted by concrete practitioners. The "Guide to Durable Concrete," developed by the American Concrete Institute Committee (ACI) 201 [14], met the three criteria and was chosen to be the factual framework of DURCON. The Guide consists of seven chapters and the subjects are given in Table 1. In the conceptual design of DURCON, four major durability problems covered by the guide were considered, freezing and thawing, sulfate attack, corrosion of reinforcing steel, and reactions between the constituents of cements and aggregates. These four problems were selected because they comprise the most persistent causes of the premature deterioration of concrete (excluding inferior concrete attributed to inadequate quality management). The known major factors controlling the response of concrete to these deterioration processes and recommendations of measures to minimize their deleterious effects are given in the Guide.

The first step in representing this knowledge was the creation of tree (hierarchy) structures. The tree structure for the knowledge of the freeze-thaw durability of concrete is illustrated in fig. 2. Then the facts were expressed in the form of production rules. The planned sequence of the stages in developing DURCON is indicated in fig. 3. After the factual structure is developed experts in concrete durability will be requested to contribute to the heuristic component of the knowledge base. Also further improvements in the knowledge base and the recommendations undoubtedly will result from workshops of experts and from users' evaluation.

It is conceivable that if DURCON proves useful, responsibility for its maintenance could be assumed by a voluntary consensus standards committee such as ACI 201, and it could be issued as a new type of guideline.

During the development of DURCON its knowledge is being partitioned into four components, each dealing with a major durability problem (freezing and thawing, sulfate attack, corrosion of reinforcing steel, and aggregate-cement reactions). Undoubtedly, some knowledge overlap will occur and, where appropriate, the individual knowledge bases will be linked or integrated. The first component of the knowledge base being developed addresses the freeze-thaw durability of concrete. A model expert system using this knowledge base is described in Section 4.

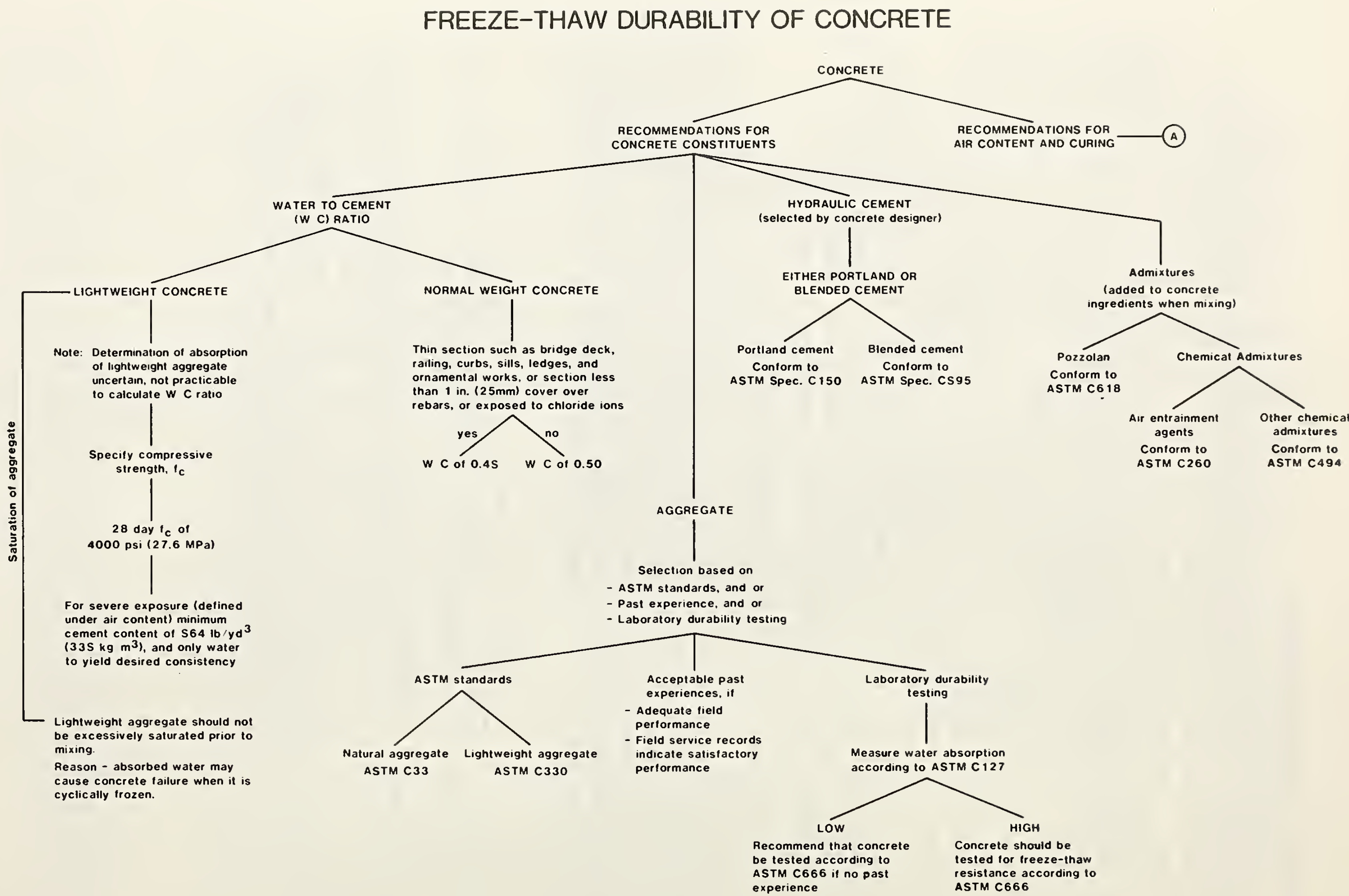

Figure 2. Tree Structure for Representing the Knowledge of Freeze-Thaw Durability of Concrete

A

RECOMMENDATIONS FOR AIR CONTENT AND CURING
(depends on severity of exposure and coarse aggregate size)

EXPOSURE

MODERATE

Defined: Outdoor exposure in cold climate where concrete will be only occasionally exposed to moisture prior to freezing and where no deicing salts are used

Exposure while curing to one or two freezing cycles while dry should meet dry requirements

Air content and f_c

f_c

Before exposure to moderate conditions, f_c of 3000 psi (20.7 MPa) should be attained

DRY

Prior to exposure to one or two cycles of freezing and thawing concrete should have f_c of about 500 psi (3.45 MPa)

SEVERE

Defined: Outdoor exposure in cold climate where the concrete may be in almost continuous contact with moisture prior to freezing, or where deicing salts are used

Exposure while curing to one or two freezing cycles while dry should meet dry requirements

Air content and f_c

f_c

Before exposure to extended freezing in severe exposure concrete should attain a f_c of 4000 psi (27.6 MPa)

ENTRAINED AIR[ab]

Nominal size of maximum aggregate		Moderate exposure Average air content	Air void spacing of 0.008 in (0.20mm)	Severe exposure Average air content
in.	mm	percent		percent
0.38	9.5	6		7.5
0.50	12.5	5.5		7
0.75	19	5		6
1.50	38	4.5		5.5
3	75	3.5		4.5
6	150	3		4

[a]Air content of plastic content measured according to ASTM C173 (volumetric method), ASTM C231 (pressure method), or ASTM C138 (unit weight test).

[b]Air void spacing may be determined microscopically by ASTM C457.

Figure 2. Continued

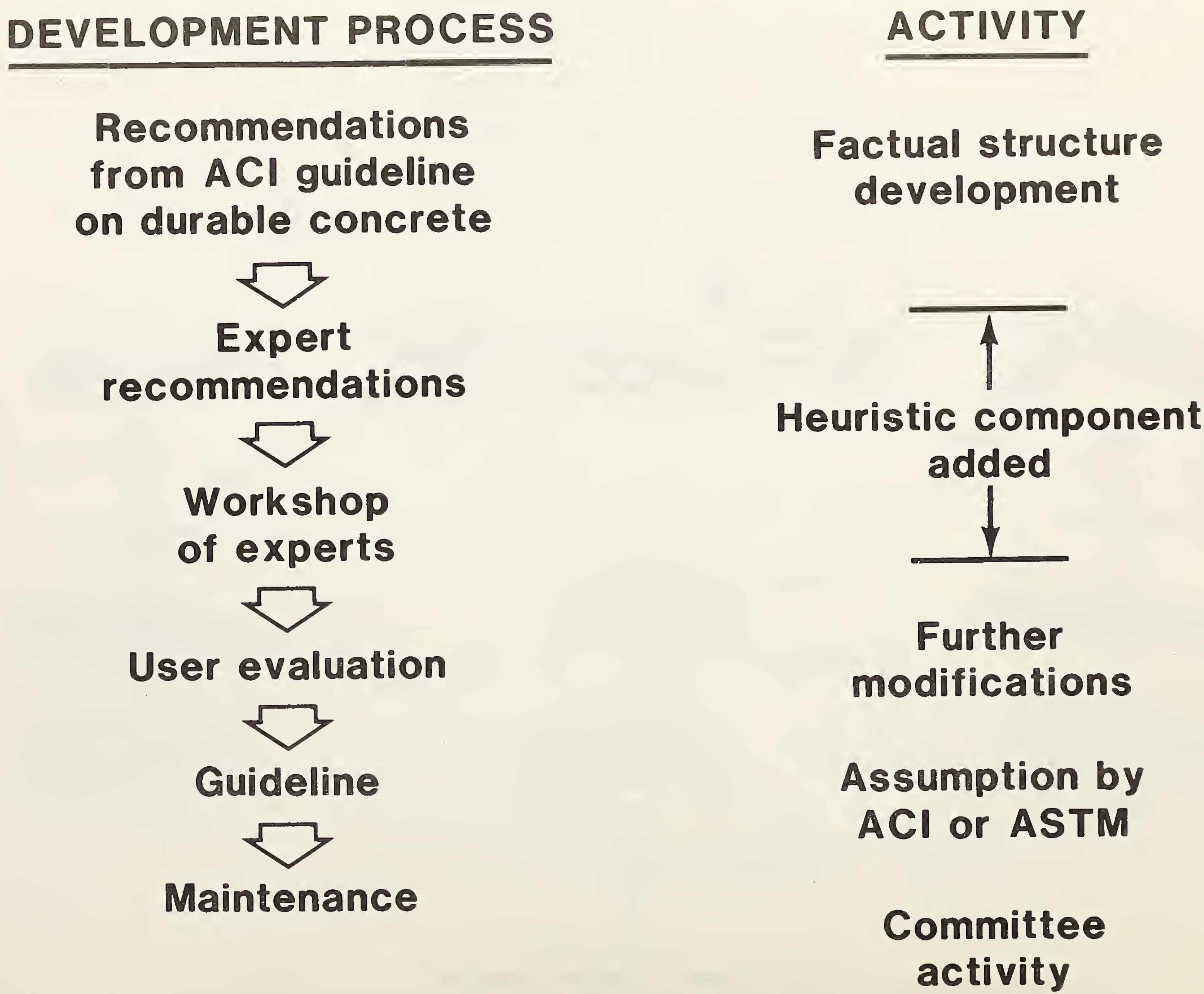

Figure 3. Sequence of the Development of DURCON

Table 1. Contents of American Concrete Institute Guide to Durable Concrete [14]

CONTENTS

Table 1. Continued

Chapter 6--Repair of concrete

6.1--Evaluation of damage and selection of repair method
6.2--Types of repairs
6.3--Preparations for repair
6.4--Bonding agents
6.5--Appearance
6.6--Curing
6.7--Treatment of cracks

Chapter 7--Use of coatings to enhance concrete durability

7.1--Surface water repellents
7.2--Plastics and elastomeric coatings
7.3--Future of coatings

4. MODEL SYSTEM USING FREEZE-THAW KNOWLEDGE BASE

4.1 Features of System

A model expert system was developed using the freeze-thaw knowledge base to test the approach described in Section 3. In the present form, the system contains 34 production rules and has the architecture shown in fig. 1. Its control system supports a forward-chaining procedure. The computer program was originally written in BASIC and subsequently converted to PASCAL. It operates on the IBM PC (personal computer) using the IBM PC disk operating system (DOS)[a].

4.2 Example of a Session

A session with the model expert system is presented in Table 2. In this session, the user specified normal-weight concrete with a portland cement. It was anticipated by the user that the concrete would be exposed to a severe freeze-thaw environment. Note that an user can request an explanation of a question. An example of a reply in response to a request for an explanation is given in Table 3.

Another feature of the system is that the answers are self-consistent. For example, if light-weight concrete is selected, then the program indicates that light-weight aggregate must be chosen. Also, if either a moderate or severe exposure condition is selected, then the program indicates that the use of air-entraining agents must be specified.

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[a] The computer hardware and software are identified in this paper to adequately describe the operation of DURCON; such identification does not imply endorsement by the National Bureau of Standards.

Table 2. User Session with Model Expert System

(The computer displays text which conveys information then requires user input in response to instructions or questions).

THIS KNOWLEDGE BASED SYSTEM GIVEN RECOMMENDATIONS ON REQUIREMENTS FOR DURABLE CONCRETE EXPOSED TO FREEZE-THAW CONDITIONS.

The Resistance of Concrete to Freeze-Thaw Cycles Is Largely Dependent on the Following:

Water-to-Cement (w/c) Ratio
Type of Structure
Exposure Conditions
Aggregate Properties
Entrained Air

In the recommendations, ASTM Standard Nos. are used, and their titles can be obtained by making the appropriate choice at the end of the session.

Please answer the questions the system will ask, as well as you can. Hit RETURN when you are ready.

Which type of hydraulic cement is to be used for this application?
1) Portland Cement
2) Blended Cement
3) Please explain the question
4) Redo a previous answer
?1

Which admixtures will be mixed with concrete ingredients?
1) Pozzolan
2) Air Entrainment Agents
3) Other Chemical Admixtures
4) 1) and 2)
5) None
6) 2) and 3)
7) 1) and 3)
8) 1) and 2)
9) Please explain the question
10) Redo a previous answer
?6

Table 2. Continued

```
Which of the following best describes this application?
 1) Light weight Concrete
 2) Normal weight Concrete with Normal Section
 3) Normal weight Concrete with Thin Section
 4) Please explain the question
 5) Redo a previous answer
?2


Which of the following describes the anticipated exposure condition?
 1) Dry
 2) Moderate
 3) Severe
 4) Please explain the question
 5) Redo a previous answer
?3


Aggregate selection will be made according to which of the following?
 1) Natural aggregate meeting ASTM C33
 2) Light weight aggregate meeting ASTM C330
 3) Labtest ASTM C666
 4) Past experience has shown the aggregate to be acceptable
 5) Please explain the question
?1


There is 60 percent chance of satisfactory performance
If not sufficient then use ASTM C666:  enter Y to use ASTM C666, any key otherwise
?y


Is the Durability Factor of 75 obtained?
 1) YES
 2) NO
 3) Please explain the question
 4) Redo a previous answer
?2
```

Table 2. Continued

Which nominal size of aggregate is to be used in this application?
1) 3/8 inch (9.5 mm)
2) 1/2 inch (12.5 mm)
3) 3/4 inch (19.0 mm)
4) 1.5 inches (37.5 mm)
5) 3.0 inches (75 mm)
6) 6 inches (150 mm)
7) Please explain the question
8) Redo a previous answer
?6

RECOMMENDATIONS

*Portland cement is required to conform to ASTM standard C150.

*Since the Durability Factor is less than 75, do test ASTM C671 (dilation test of concrete subjected to freezing) with the specimens conditioned as stipulated in ASTM C682. If it does not pass, reject the aggregate.

*With 6-inch (150-mm) aggregate selected for severe conditions, the percent of entrained air should be 4.0 percent. The only exception to the above conclusion is the possibility that the aggregate is immune to freezing in sizes up to 1 inch. (Consult the following paper for assistance in identifying such aggregates: Verbeck, George, and Landgren, Robert, Influence of Physical Characteristics of Aggregate on the Frost Resistance of Concrete,Proceedings, ASTM, Vol. 60, 1960.) ASTM test methods for air content determination require that the concrete sample be wet-sieved over a 1.5-inch sieve before test. The percent of entrained air in the sieved specimen should be 5.5 percent.

Air void spacing must be 0.008 inch (.20 mm)

*For applications using normal weight concrete for normal sections the recommended water/cement ratio is 0.50.

*Concrete for severe exposure conditions should have a F_c of about 500 psi (3.45 MPa) prior to one or two cycles of freezing and thawing while curing. It should attain a F_c of about 4000 PSi (27.6 MPa) before exposure to severe conditions.

Table 3. Example of an Explanation of a Question in DURCON

DURCON QUERY:	Which of the following best describes the anticipated exposure condition? 1) Dry 2) Moderate 3) Severe 4) Please explain the question 5) Redo a previous answer
USER RESPONSE:	4
EXPLANATION:	The definition used for dry is indoor exposure or well protected from moisture and freezing. Moderate is an outdoor exposure in cold climate where the concrete will be only occasionally exposed to moisture prior to freezing and where no deicing salts are used. Severe is an outdoor exposure in a cold climate where the concrete may be in almost continuous contact with moisture prior to freezing, or where deicing salts are used.

5 SUMMARY

This is a progress report on the development of DURCON, an expert system for making recommendations on the selection of constituents for durable concrete. Four major durability problems are being addressed, freeze-thaw damage, sulfate attack, corrosion of reinforcing steel, and cement-aggregate reactions. The factual knowledge base for DURCON is being based on the ACI Guide to Durable Concrete. Heuristic knowledge is provided by experts on concrete durability.

The knowledge base dealing with the freeze-thaw resistance of concrete has been developed. A model expert system giving recommendations for concrete exposed to freeze-thaw conditions has been prepared and demonstrated. At present, it has 34 production rules and uses a forward-chaining control system.

6 ACKNOWLEDGEMENT

The authors wish to acknowledge the encouragement of and helpful suggestions by Dr. Geoffrey Frohnsdorff, National Bureau of Standards, which contributed significantly to the development of DURCON. The assistance of Mr. Paul Kleiger, Chairman of ACI Committee 201, Durability of Concrete, in providing a forum for discussing DURCON is greatly appreciated. The assistance of Mr. Robert Philleo, former president of the ACI and Private Consultant, in developing the freeze-thaw knowledge base also is acknowledged.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This is a progress report on the development of DURCON an expert system to give recommendations on the selection of constituents for durable concrete. Four major concrete deterioration problems will be covered when the DURCON system is completed; freeze-thaw, sulfate attack, corrosion of reinforcing steel, and cement-aggregate reactions. The factual knowledge base for DURCON is based on the American Concrete Institute Guide to Durable Concrete. Heuristic knowledge is being obtained from experts on the durability of concrete. The approach being taken in developing DURCON is discussed. Then a model expert system for concrete exposed to freeze-thaw conditions is described.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Aggregate, Artificial Intelligence, Concrete, Corrosion, Durability, Expert System, Freeze-Thaw, Knowledge-Based System, Sulfate Attack

13. AVAILABILITY

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